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AERODYNAMIC ISSUES IN THE DESIGN OF HIGH-LIFT SYSTEMS FOR TRANSPORT AIRCRAFT

by

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SUMMARY

The design of the high lift system has a profound effect on the sizing and total performance of transport aircraft, both civil and military. ~~The purpose of~~ this paper ~~is to~~ first reviews the fundamentals of high-lift system design and the phenomena that govern their performance. A review of the computational methods available to the high lift designer, with examples of their validity, is then presented. New developments in flow diagnostic techniques are reviewed. Finally, examples of several Boeing high-lift design efforts are presented. Emphasis is placed on the use of computational aerodynamic methods and the synergistic effect of using these methods in parallel with testing. Finally a list of today's ten most important issues is presented.

NOMENCLATURE

AePP = Aerodynamic Prediction Program
AR = aspect ratio, b^2/S
b = wing span
c = basic cruise wing or airfoil chord
$\bar{c}$ = average wing chord S/b
c_d, c_l, c_m = two-dimensional (section) drag, lift and pitching moment coefficients, force/qc and moment/qc^2
C_D, C_L, C_M = three-dimensional configuration drag, lift and pitching moment coefficient, force/qS and moment/qSc
C_μ = blowing coefficient $M_j V_j / q_\infty S$
C_p = pressure coefficient, $\Delta p/q_\infty = (P_{local} - P_\infty)$
DVM = Distributed Vorticity Method
H = boundary layer form parameter, δ^*/θ
L/D = ratio of lift to drag
M = Mach number
M_j = jet mass flow rate
P = static pressure
q = dynamic pressure
Rn = Reynolds Number
SABS = Subsonic Analysis Section System
S = Wing area
T = Thrust
t = airfoil thickness
V = Velocity
V_j = jet velocity
W = Weight
x = longitudinal coordinate
y = lateral coordinate
α = angle of attack
Δ = differences (residuals)
δ_f = flap deflection
δ^* = boundary layer displacement thickness
θ = boundary layer momentum thickness
η = non-dimensional spanwise wing station $2y/b$
Λ = sweep angle measured at wing quarter chord

Subscripts

eff = "effective" viscous condition
exp = experimental value
f = flap
geo = geometric value
max = maximum
min = minimum
∞ = free stream conditions
r = point at which pressure recovery to freestream conditions begin on an airfoil
visc = viscous

Superscripts

$(\wedge)$ = adjusted or scaled quantity
$(*)$ = critical section

INTRODUCTION

It has been a decade since A.M.O. Smith, then of the McDonnell-Douglas Aircraft Corporation, presented his Wright Brothers Lecture[1] entitled "High-Lift Aerodynamics" (based on an earlier AGARD Lecture[2]) to the American Institute of Aeronautics and Astronautics. In the flood of technical papers which have documented the extraordinary progress of aeronautical science over the past forty years, A.M.O. Smith's paper stands as a true classic. In addition to greatly clarifying the physics of important aspects of high-lift aerodynamics, Smith clearly set the stage for much of the subsequent work in this discipline.

The history of high-lift technology can be traced in the application of high lift devices on Boeing aircraft over the past forty years shown in Figure 1. Since the authors have been involved in at least part of this development at Boeing, we necessarily approach our subject from that somewhat parochial viewpoint. As will be described in later sections of this paper, much of the progress demonstrated in Figure 1, was achieved by a process best characterized as "enlightened cut-and-try." This was aided in its later phases by slowly improving but still fairly elementary analytical methods. Testing was conducted almost universally in wind tunnels operating at Reynolds numbers at least an order of magnitude lower than actual flight conditions. Such has been the general state of affairs until very recently throughout the industry.

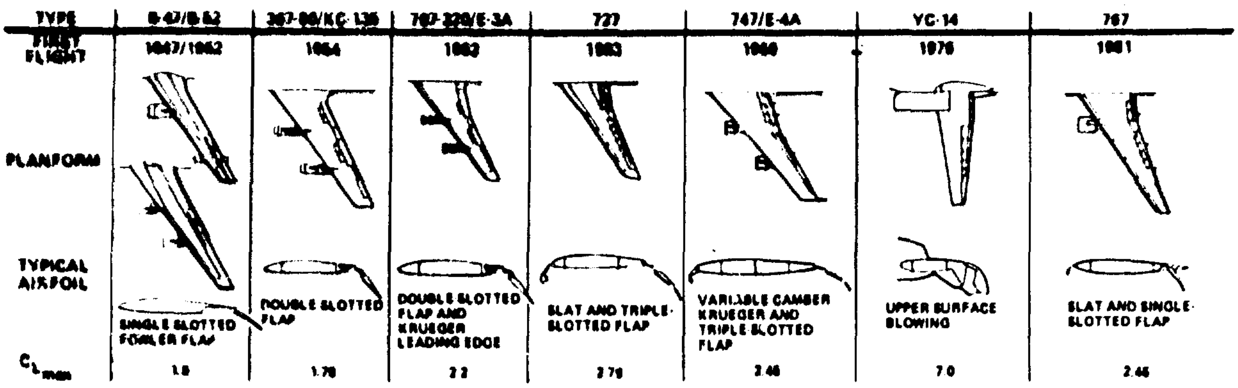

Figure 1. Trends in Boeing Transport High-Lift System Development

Advances over the past fifteen years in both computational methods, including use of inverse methods, and experimental flow diagnostic technology, have made possible a high lift system design process quite different than that which has relied largely on experience, intuition and experimentation alone. The further development and enhancement of this modern high-lift design process is one of the major issues referred to in the title of this paper.

There were several objectives in preparing this paper. These include:

- A review of some of the factors which influence the design of modern transport aircraft (both civil and military) and the effect of high-lift system performance on the overall design of such aircraft.
- The assessment of progress in the understanding and methodology development which has occurred in the decade since A.M.O. Smith presented his classic AIAA Wright Brothers Lecture.
- The demonstration of a modern approach to the solution of selected practical high-lift system design problems.
- To list the major issues, both practical and theoretical, which still confront the high-lift aerodynamicist as perceived by the authors.

As numerous authors have pointed out, the topic of high-lift aerodynamics covers an enormous range of flight vehicle types operating under a wide range of Mach and Reynolds number condition. While the entire topic holds a fascination for the authors, it is necessary to limit the scope of this paper to high-lift issues relating specifically to transport aircraft during "normal" take-off and landing.

HIGH-LIFT AERODYNAMIC ISSUES

The fundamental issues to be addressed in this paper are:

- Recognizing that maximizing the maximum lift coefficient is a simplistic view of the high-lift system design problem, what are the appropriate high-lift system aerodynamic design criteria for the anticipated range of moderate-to-large sized transport aircraft?
- In the light of our present theoretical understanding, how much practical performance, in terms of maximum lift coefficient, remains to be extracted from a truly optimized "conventional" high-lift system i.e. one which relies on passive boundary layer control based on geometry alone?
- What tools are available to design practical, efficient high-lift systems, and what additional tools do we need?

Before addressing any of the questions listed above, it is useful to compare and contrast the general design objectives and constraints of military and civil transport aircraft, particularly as these factors may influence the designer's options regarding high-lift system design. A partial summary listing of these design objectives/constraints is presented in Table 1.

In reviewing the criteria listed in Table 1, it should be noted that the general civil transport aircraft design problem is driven largely by economic considerations with an equally strong concern for safety. Thus, the design is generally optimized first and foremost for cruise efficiency. The objective of the complementary high-lift design effort is to produce a system which will allow a cruise optimized configuration to adequately meet take-off and landing requirements safely and reliably. It should also be noted that in normal commercial operations, the operating environment is relatively benign (aside from meterological considerations) involving paved runways, adequate to excellent air traffic control and landing aides, and well established maintenance facilities.

The military transport airplane designer appears to face a somewhat different problem. In principle, the dominant design criterion is successful mission accomplishment. While basic economic criteria such as range, payload and cruise speed, as an index of productivity, play important roles in layout and sizing, mission accomplishment simultaneously places very heavy demands on the high-lift system designer. In this case, mission accomplishment may require that the aircraft be able to operate

Issues	Civil	Military
Dominant design criteria	• Economics and safety	• Mission accomplishment and survivability
Performance	• Maximum economic cruise • Minimum off-design penalty in wing design	• Adequate range and response • Overall mission accomplishment
Airfield environment	• Moderate-to-long runways • Paved runway • High-level ATC and landing aides • Adequate space for ground maneuver and parking	• Short-to-moderate runways • All types of runway surfaces • Often Spartan ATC, etc. • Limited space available
System complexity and mechanical design	• Low maintenance—economic issue • Low system cost • Safety and reliability • Long service life	• Low maintenance—availability issue • Acceptable system cost • Reliability and survivability • Damage tolerance

Government regulations and community acceptance	• Must be certifiable (FAA, etc.)
	  • Safety oriented
	• Low noise mandatory
		• Military standards
		  • Performance and safety
		  • Reliability oriented
		• Low noise desirable
		  • Good neighbor in peace
		  • Detectability in war

Table 1. Transport Aircraft Design Objectives and Constraints

from battle damaged and/or primitive airfields, sometimes in a hostile environment. In exchange for these more demanding criteria, the military high-lift systems designer has more system options at his disposal in that presently "difficult to certify" powered lift schemes become viable - if they can be shown to be sufficiently reliable, maintainable and insensitive to battle damage.

It is perhaps ironic that in the extended "peacetime" environment, many of the civil aircraft design criteria play a larger role in military design requirements than may be fully appropriate. As examples one may cite budgetary constraints which demand low initial cost biasing the design in favor of minimum size and weight and low fuel burn to minimize routine operating and training flight costs. Also increasing concern for community acceptance carries potential performance penalties in terms of concessions for noise reduction and engine emissions. The longer military transport aircraft serve the function of contributing to maintaining peace, the more civil type design criteria become important in the overall balance.

The discussion so far indicates that while the basic design criteria for civil and military aircraft are somewhat dissimilar, the high-lift system design problem still resolves into several common issues. Fundamentally, the high-lift system must allow the aircraft to achieve adequate performance - both at landing and take-off (Fig. 2 & 3). Experience indicates that for CTOL aircraft the dominating factor for take-off is climbout L/D and for landing, C_{Lmax}. As shown in Fig. 4, approach speed has a value in itself, not only as a performance variable, but as an important safety factor. Even though the level is dependent on the operational environment and level of technology the general trend holds true.

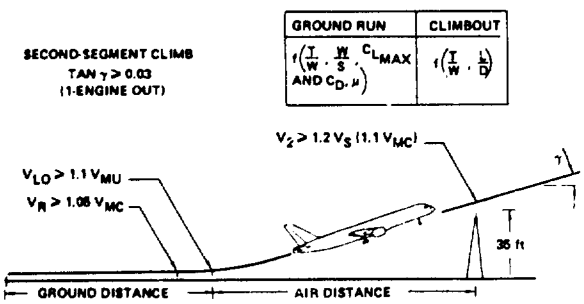

Figure 2. Takeoff Profile

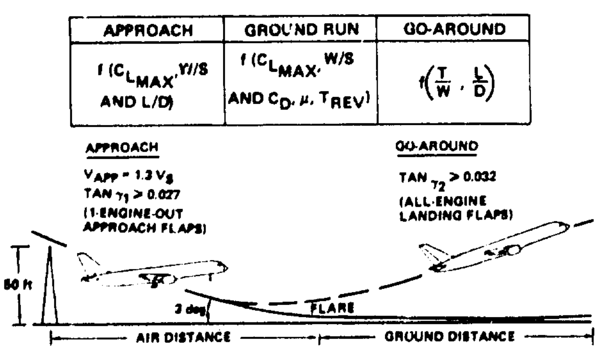

Figure 3. Landing Profile

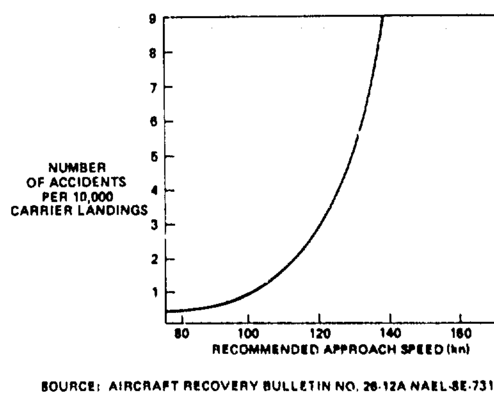

Figure 4. Influence of Aircraft Approach Speed on Carrier-Landing Accidents

Finally, it is obvious that whether the primary concern is safety and certifiability, or mission accomplishment, the high-lift system must be reliable. Thus the strongest bias must be in favor of simplicity. In both the civil and military case, maintainability implies availability, and simplicity has a very strong leverage on these factors. Vulnerability to battle damage is intrinsic in mechanically complex systems, and the attraction of a very large number of mechanically complex augmented/powered lift schemes begins to vanish despite the potentially large increments in lift achievable with such systems under benign conditions.

THE INFLUENCE OF HIGH-LIFT SYSTEM PERFORMANCE ON TRANSPORT AIRCRAFT SIZING

Having discussed in general terms the objectives and constraints on civil and military transport aircraft design, it now remains to demonstrate in more detail how high-lift system performance may influence the sizing of such aircraft. While a comprehensive discussion of this topic is far beyond the scope of this paper, two examples, one civil and one military, will serve to illustrate the complex trades to be made in selecting an appropriate high-lift system for such aircraft.

An Energy Efficient Transport

The first example selected is based on work for the NASA Energy Efficient Transport EET program (ref 3 & 4). Most of the analysis and design methods used in this study were developed under Boeing Independent Research and Development (IR&D) funds and will be described in some detail in later sections of this paper. The intent of the present discussion is to demonstrate the dominant high-lift system requirements which emerge in the course of a typical preliminary design exercise for a modern commercial transport airplane.

Typically the wing for a new design is sized to satisfy cruise considerations, including initial cruise altitude, cruise Mach, buffet margin, etc., and low-speed, high lift considerations such as approach speed and takeoff field length.

The results of a typical "thumb print" analysis of the Boeing baseline EET configuration (Fig. 5) is summarised in Fig 6. In the study, size consequences of three discrete optimization indicier were explored. These were:

- Minimum take-off gross weight which would presumably result in an aircraft of minimum airframe acquisition cost.
- Minimum block fuel burned; of major interest to the EET program.
- Minimum direct operating cost (DOC); the traditional index of interest to airline operators.

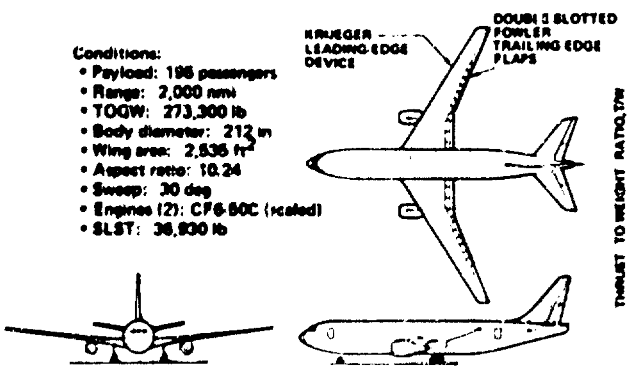

Figure 5. Baseline Airplane

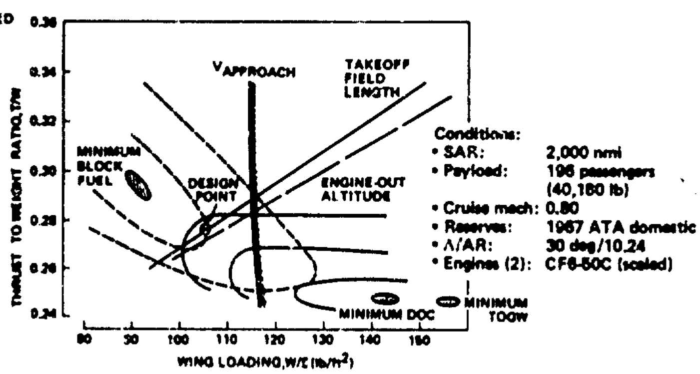

Figure 6. EET Baseline Design Selection Chart

The conclusions drawn from the results shown in Figure 6 were:

- Both the minimum weight and minimum DOC design points were very far away from the minimum fuel burn design point. The minimum block fuel airplane required a much larger wing and engines than either the minimum DOC or minimum weight designs.
- A conservative, state-of-the-art double-slotted flap/variable camber Krueger leading edge high-lift system more than adequately met approach speed and landing field length requirements.
- The dominant constraint on sizing, leading to a compromise design point skewed in favor of the minimum block fuel condition, was take-off field length (and hence take-off lift-drag ratio) followed very closely by a nominal 12,000 ft. engine-out altitude constraint.

From this study it is clear that a priori assumptions regarding high lift system performance requirements for a new design are inappropriate. Care must be taken to evaluate the range of conditions (take-off, landing, initial climb, etc.) in which high lift system performance may be critically important before investing much resource in developing a high lift system.

A Military Short-Haul Transport (MST)

This example will use results from a feasibility study for a Medium STOL Transport (MST) which led to the Advanced Medium STOL Transport (AMST) program under which the Boeing YC-14 and McDonnell-Douglas YC-15 were developed. The fundamental performance requirements were that the airplane fly a radius mission with a 28,000 pound payload operating into and out of a 2,000 foot long airfield at the mission midpoint. The field was assumed to have an elevation of 2500 feet and an ambient temperature of 93°F. Operation had to consider failure of the most critical engine during takeoff and landing. In addition, the aircraft had to carry 38,000 pounds of payload for 2600 nmi while operating from longer runways.

One of the fundamental considerations was selection of a high-lift system concept. Figure 7 shows a map of airplane design solutions for the design radius mission for a four engine airplane using a high lift system having a maximum lift coefficient of 4.0. Superimposed on this map are takeoff and landing field length and engine-out climb gradient limits. The selected design is the lowest takeoff gross weight solution satisfying all of the design constraints.

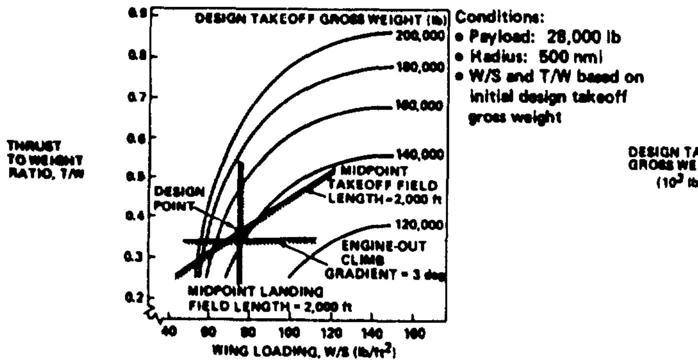

Figure 7. MST Design Sizing

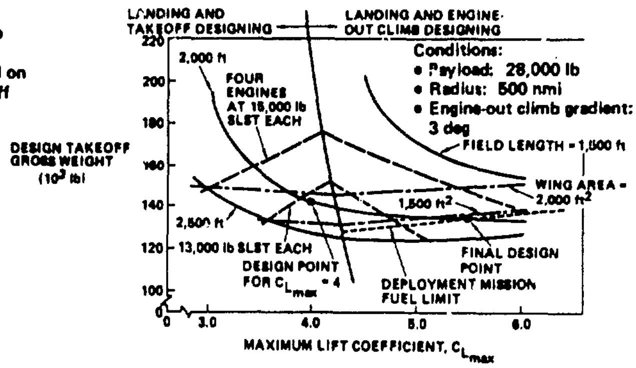

Figure 8. Effect of Lift Capability on MST Design

This process can be repeated for high lift systems having varying lift capability accounting for the obvious fact that the weight of a high lift system increases as its maximum lift increases. These results are shown in Figure 8. The design point determined from Figure 7 is noted. Airplane size for a 2000 foot mid-point field length continues to decrease as maximum lift coefficient is increased up to $C_{L\ MAX}$ of about 6.0. However, the wing volume available for fuel tankage to fly the deployment mission now becomes a limit. The selected design had a $C_{L\ MAX}$ of 5.5 and a design gross weight of 235,000 pounds. This study was conducted in 1976 with the propulsion and aerodynamics technology available at that time. If it were repeated today the results would differ but the process by which the airplane was sized and the high lift system selected would remain the same.

THE LIMITS OF HIGH LIFT

Before assessing the state of high lift aerodynamics, it is useful to establish an "upper bound" against which one can compare the "practical" limits in design. A.M.O. Smith discussed these limits a decade ago and it is merely necessary to summarize his discussion with the inclusion of Figure 9.

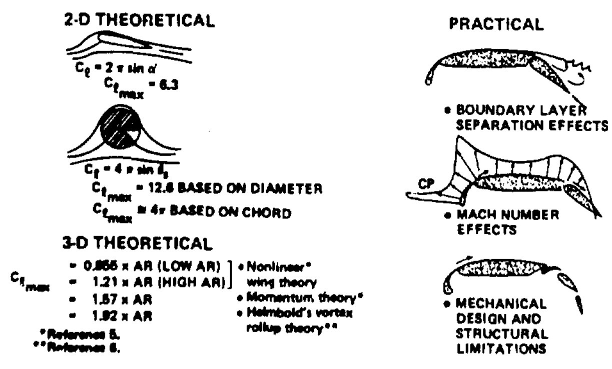

Figure 9. $C_{\ell_{max}}$ Limits

The left hand side of Figure 9 shows a number of theoretical two- and three-dimensional bounds which have been developed for maximum lift generating capability of "ideal" configurations. The right hand side shows several of the practical factors which may severly limit achievable performance. In addition to obvious limits imposed by viscosity, compressibility and mechanical constraints on two-dimensional sections, further losses are incurred in applying such sections to three-dimensional configurations. These effects include the adverse influence of wing sweep, the fact that the entire wing span of most practical configurations cannot be taken up with idealized high-lift systems, and the existence of necessary supporting structures which may produce local interference and boundary layer contamination effects. Besides reducing the lift these factors also tend to increase drag, and the effects on achieved lift-to-drag ratio for a typical transport are demonstrated in Figure 10. The influence of wing sweep on the achieved maximum lift performance of a variety of modern transport aircraft with conventional high-lift systems is shown as a function of high-lift system complexity in Figure 11.

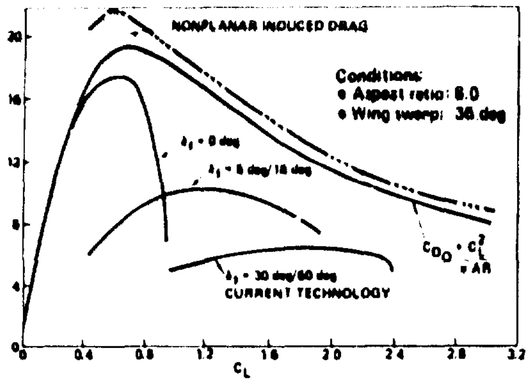

Figure 10. Potential Performance Improvement for Mechanical High-Lift Systems

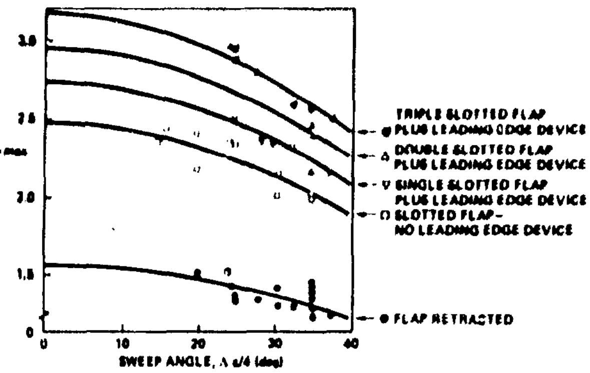

Figure 11. Statistical Analysis of Maximum Lift Coefficient for Transport Aircraft

If one now plots (Figure 12) the theoretical limits specified in Figure 9 and identifies the region of maximum lift coefficient achieved with unpowered high-lift systems, one sees the huge gap between achieved levels and the theoretical limits. It is here that powered lift schemes have application. A very useful discussion of this range of powered lift schemes is presented by Foster[7] as a companion piece to A.M.O. Smith's discussion. A recent paper by Loth & Boasson[9] provides an update on Foster's discussion in addition to providing a description of practical STOL aircraft operational requirements vis-a-vis powered lift system performance characteristics.

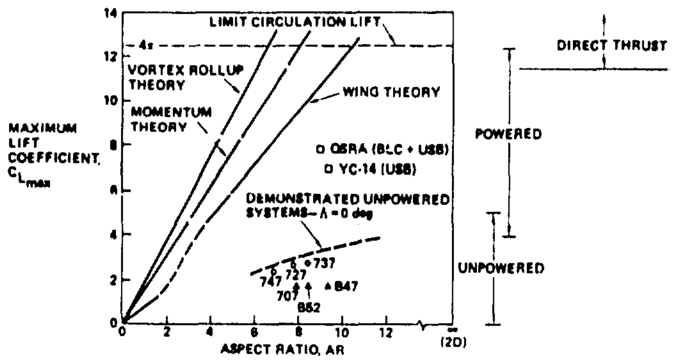

Figure 12. Limits of Maximum Lift Coefficient

Having noted the approximate boundaries of the feasible in terms of maximum lift coefficient as shown in Figures 9 and 12, it has been shown that the practical limits of maximum lift demonstrated for unpowered high-lift systems is far below the theoretical limit, even when systems of considerable mechanical complexity are employed. Of the practical reasons for this huge discrepancy noted earlier, by far the dominant factors limiting maximum lift are viscous effects and flow separation.

In view of the design space available within Figure 12 it is possible to describe a hierarchy of ways to control the boundary layer on a wing surface.
These are:

- Passive Boundary Layer Control by Contour Shaping and Variable Geometry. This approach is the most subtle; so much so that one sometimes forgets that it is a form of boundary layer control. The limits of boundary layer/circulation control for both single and multielement airfoils has been greatly clarified in the past two decades, perhaps foremost by A.M.O. Smith and his co-workers at Douglas, specifically R. H. Liebeck[9]. The full extensions of this work to three dimensional flows remains to be accomplished however.

- Power Augmented Boundary Layer/Circulation Control. Once one has approached the limit of maximum lift achievable by passive boundary layer circulation control through contour shaping including the mechanical complexity of multielement airfoils and wings, the next level of performance increase is achieved by using small amounts of auxiliary power to (1) increase the energy of the boundary layer by blowing or (2) remove all or part of the boundary layer by suction. As shown in Figures 13 & 14 there are a wide variety of schemes to accomplish either of these objectives. In all cases the objective is to delay the onset of separation and thus produce an increase in maximum lift.
The particular application under study and the indices of merit by which the overall configuration will be judged will determine when substitution of a simple blowing/suction system would be preferable to adding yet another flap element to an already complex passive/mechanical system. At the other extreme, when does one reach a blowing/suction limit and one of the more powerful jet flap/circulation control schemes (Figure 15) becomes a better way to produce still higher lift coefficients.

- Powered Lift. As the required lift coefficients increase, we again pass through a transition region to the powered lift concepts involving the propulsion system as an integrated part of the high-lift system (Fig 16). Two types of powered lift concepts may be identified. The first separates the propulsion and circulation lift system and provides only direct jet lift, e.g., vectored thrust or lift engines. The second combines the propulsion and circulation

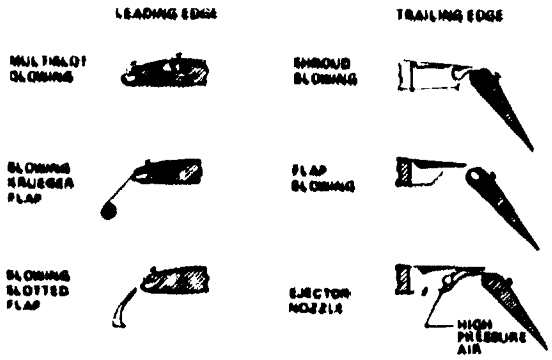

Figure 13 Blowing BLC Concepts

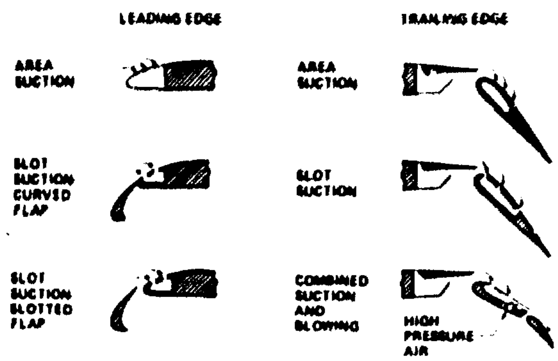

Figure 14. Suction BLC Concepts

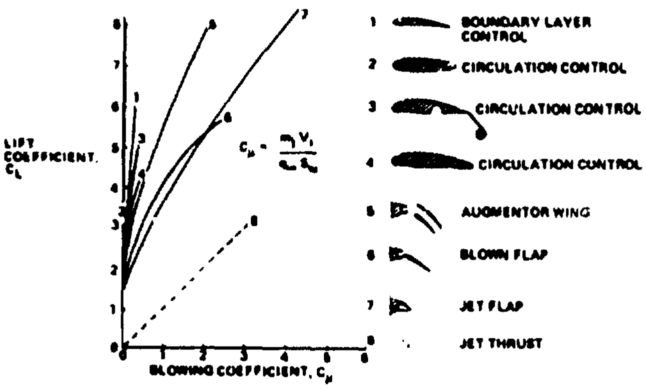

Figure 15. Powered High-Lift Performance for Various Wing Configurations (ref. 8)

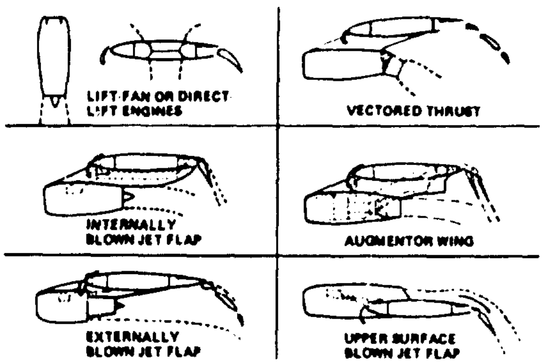

Figure 16. Powered Lift Concepts

lift system into a jet-flap type powered lift system. The augmentor wing, externally blown flap, and upper surface blown flap can all be considered subsets of the jet-flap concept.

While identifying the various lift enhancing schemes aids in discussing the multitude of possibilities and gives some flavor for the general level of lift performance achievable, it still does little to establish which is "best" for a particular application. This will depend on the payoff function, (e.g., DOC, LCC, Trip Fuel, etc;), the payload range of the airplane, and off design mission requirements.

While the probable trends in high-lift system development for long field-length transports can be described with some assurance, the same cannot be said for the case of STOL transport aircraft. What does emerge from the preceeding discussion is that there are a number of promising ways to achieve the high lift performance required for any reasonable STOL mission. All of the powered lift systems mentioned previously have been incorporated into flight hardware. The pure jet flap on the Hunting 126, the augmentor wing on a Boeing/NASA modified Buffalo, the externally blown flap on the McDonnell-Douglas YC-15, and the upper surface blown flap on the Boeing YC-14 and Boeing/NASA QSRA are some examples.

Passive/mechanical BLC high-lift systems are likely to be the norm for long range, moderate to long field length transport aircraft into the forseeable future. It must continue to form a major element of a discussion of high-lift technology. There is still progress to be made in the design of such systems.

The design of powered lift aircraft requires that more variables be considered than in the design of more conventional airplanes since STOL airplanes encounter control and handling qualities problems more severe than conventional airplanes. It must be noted that solutions to these problems have been found in specific design applications.

An example of one practical limit is the angle of attack of a particular configuration required to generate a given lift level. Here the coupling between approach speed, glide slope angle, and angle of attack as it influences pilot visibility and hence decision time, is shown schematically in Figure 17.

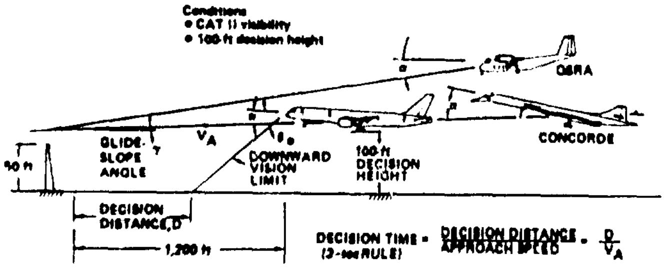

Figure 17. Effects of Glideslope and Angle-of-Attack on Decision Time

In view of the factors discussed, it is the authors' present opinion that of the many powered lift schemes presently available to choose from, relatively few offer the prospect of satisfactorily meeting the performance requirements and many constraints of practical STOL transports. Experience with the upper surface blowing (YC-14, QSRA) and externally blown flap (YC-15) indicates that these approaches could be developed into satisfactorily reliable and economical vehicles for both civil and military applications.

With the overview discussion of practical issues in high-lift technology provided above, it is now possible to discuss the state-of-the-art in methodology available to the high-lift system designer.

BOEING RESEARCH IN HIGH-LIFT TECHNOLOGY

A comprehensive survey of the industry-wide research devoted to solution of the theoretical problems in high-lift technology identified by AMO Smith a decade ago is a prohibitive task. Instead we choose to outline Boeing research devoted to this topic in the past decade and cite limited examples of related significant work by others. Further, the majority of the discussion is limited to mechanical systems since little theoretical work has been done at Boeing in recent years on powered lift systems.

While fully realizing that the approach taken here represents a rather parochial view of a very broad topic, it is the authors' opinion that the Boeing research effort is representative of the current state-of-the-art.

The Boeing Company research effort has been directed at developing a range of powerful tools for the design and analysis of transport type aircraft operating in low-speed/high-lift conditions. The basic objectives of this, largely company-funded, long term effort have been:

- To develop computational methods for the analysis and design of high-lift configurations.
- To provide improved flow diagnostic techniques and experimental data bases to support computational methods development.
- To apply these new tools to practical design problems to assess their capabilities and to guide further basic method development.

Thus over the past decade, the basic approach has been a balanced one encompassing theory, experiment and applications.

POTENTIAL FLOW SIMULATION OF THREE DIMENSIONAL MULTIELEMENT WINGS

Potential flow simulation of transport aircraft with high-lift devices deployed is an essential step in the evolution of a rational analytic design capability and also serves as the foundation for viscous/vortex flow simulations of these configurations. In addition, until a full three-dimensional viscous analysis capability becomes available, a three-dimensional potential flow analysis/design capability remains an essential cornerstone of an analytic high-lift design procedure. The work has been devoted largely to two computer programs: A Distributed Vorticity Lifting Surface Theory, and extension of the PAN AIR code to th modeling of high lift configurations.

Computational methods for the analysis and design of three-dimensional wing and wing-fuselage configurations have evolved over the years from simple lifting line techniques which made very restrictive assumptions about the geometry of the configuration and the flow conditions, to very sophisticated and general panel methods. The most sophisticated of the newer methods (e.g. PAN AIR, ref. 10) offers the designer a very powerful potential flow analysis tool. However the difficulty in using these methods because of the very precise geometric definitions required especially for multielement high-lift configurations, coupled with the expense of running such codes, has precluded their wide spread use in high-lift applications. Only in cases where detailed pressure distribution information is required are they being used. Parenthetically we note that in our opinion the concern with computer costs is overstated. The actual machine costs of obtaining a solution are substantially less than the cost of the engineering labor required to prepare the problem for input to the computer. In may cases the money spent in the search for computer efficiency might be better spent in making the code more user friendly.

In many practical problems the analyst/designer primarily requires accurate information on items such as net lift, pitching moment, induced drag and span loading - items available in principle from a potential flow analysis of less sophistication than a full higher order panel method.

In 1975, M. I. Goldhammer began to develop the elements of an advanced lifting surface method (ref. 11). Goldhammer developed a very powerful version of his program aimed specifically at the multielement wing/body problem and possessing a great deal of automation aimed at easing the burden on the user of the code.

Two different lifting-surface theories are included in Goldhammer's computer program. A non-planar, non-linear distributed vorticity method (DVM) is the primary method while a simpler vortex lattice approach is available as a user option. The primary technique represents the thin wing by a continuous sheet of distributed vorticity which lies on the mean camber surface. The vorticity distribution used is continuous in the chordwise direction and is piecewise constant in the spanwise direction (Fig 18). Special treatment is given to the chordwise vorticity distribution. The loading at the wing leading edge is modeled to be infinite, which is consistent with the thin wing approximation. The DVM technique also explicitly satisfies the Kutta condition by forcing each trailing edge loading to zero.

Full provision is made for multielement wings with part span flaps. A two-dimensional algorithm is used by the program to specify the downstream path of shed vorticity. The program is highly automated, and the user need specify only gross geometric parameters for multielement wings (e.g. planform, twist, camber, flap deflection) the program then generating its own detailed vorticity networks.

In addition the overall method includes a modified slender-body theory representation of the fuselage, which is adequate for modeling wing lift carry-over effects and the body contribution to pitching moment.

The program also includes three-dimensional design (inverse) capabilities. An induced drag minimization technique is included, for example, based on the Lagrange multiplier technique.

Since release of the production version of the basic code in 1978, the program has achieved widespread acceptance within the Boeing Company. As part of the code development and subsequent validation effort a number of test-theory comparisons have been made, with the results shown in Fig. 19 being typical of those obtained.

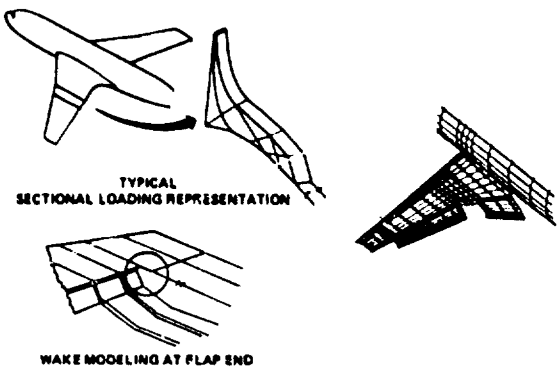

Figure 18. DVM Lifting Surface Analysis for High-Lift Configurations

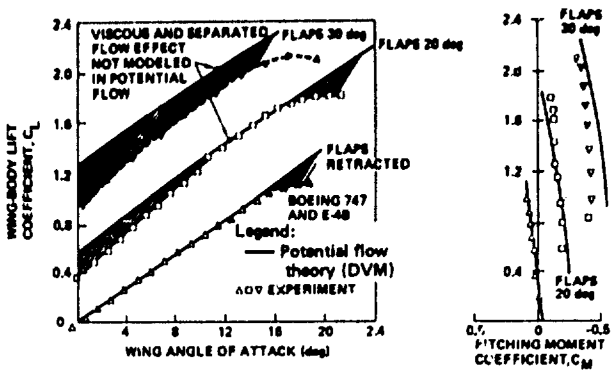

Figure 19. Typical Distributed Vorticity Method (DVM) Results

The excellent agreement in both lift curve slope and lift level demonstrate the satisfactory nature of the thin wing approximation when no separation occurs. The usual explanation for these good results is that neglect of both thickness effects and boundary layer build-up ("viscous decambering") are counter effects which approximately cancel each other. This mutual cancellation effect deteriorates at higher flap deflections and most particularly when there is significant partial separation of the flow.

The DVM Lifting Surface Theory program does a remarkably good job of predicting net lift, pitching moment, induced drag and span loadings for a wide class of high-lift configurations. However, it does not provide two important capabilities. It cannot give detailed potential flow pressure distributions and it does not have the ability to model details of the configuration such as wing/body junctions or nacelle/strut combinations.

To obtain such additional detailed information, one must resort to more sophisticated methods such as PAN AIR. While application of panel method technology to the cruise configuration has been widely successful, its extension to high-lift configurations has not. Early attempts to model multielement wings using panel methods led to major discrepancies in prediction of both lift level and lift curve slope. These difficulties have generally been attributed to deficiencies in the way early panel methods handled the Kutta condition and uncertainties in proper modelling of multiple wakes and vorticity shed from part-span flap edges.

With final production release of the Lifting Surface Theory, attention turned to the problem of adapting the lessons learned regarding wake modelling to the advanced panel method codes. In addition, the difficulty of paneling the complex geometries of multielement wings has been solved. A typical result compared with experimental data from ref. 12, is shown in Fig. 20.

The central purposes of this work with PANAIR have been:

- To extend the power of the full panel method to include high-lift configurations.
- To provide potential flow pressure distribution data essential to future development of a full three-dimensional viscous flow analysis capability for multielement wings.
- To provide a theoretical tool which provides some insight into the inviscid aspects of large scale vortex/airframe interaction problem.

An early PANAIR test-theory comparison for the case of a swept wing with part-span, triple-slotted flaps and leading edge slat is shown in Fig. 21.

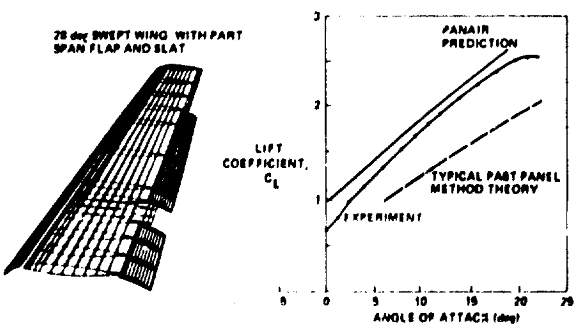

Figure 20. PANAIR Modeling of Wings With High-Lift Devices

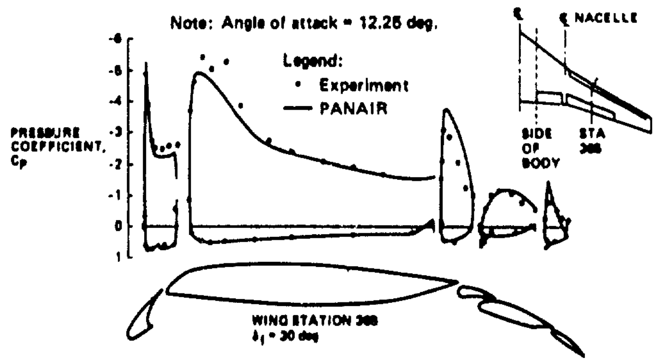

Figure 21. Test-Theory Comparison of PANAIR Modeling of a Boeing 737-300 Wing

ANALYSIS AND DESIGN OF MULTIELEMENT HIGH-LIFT SYSTEMS IN A VISCOUS FLOW

The performance of high-lift systems is largely limited by viscous flow phenomena and subsequent separation. Because of the inordinate difficulty of computing viscous flows in three-dimensions, particularly those which may occur on complex multielement wings, the bulk of past effort has been devoted to the development of a full viscous flow analysis and design (inverse) capability for two-dimensional, multielement airfoil sections. It was in the clarification of the physics of multielement airfoils that A.M.O. Smith made one important contribution to high-lift technology.

The flow around high lift airfoils is characterized by many different inviscid and viscous flow regions as illustrated in Figure 22. In particular, the existence of confluent boundary layers and the regions of separated flow distinguish the high lift airfoil problem from the aerodynamic problem of airfoils at normal operating conditions. The characteristics of the various flow regions must all be calculated. Futhermore, the prediction of transition from laminar to turbulent boundary layer flow, the prediction of the onset of boundary layer separation and the effects of large scale separation from one or more airfoil elements are a necessary part of any general high-lift analysis computer program.

In addition to allowing a pure analysis of a given geometry, a truly utilitarian code should also contain an inverse capability, which allows one to extract an airfoil shape from a specified pressure distribution. In addition methodology should exist which would allow the design/optimization of this pressure distribution in a viscous flow.

The development of this full capability has been a central objective of the Boeing high lift research effort since 1975. The outcome has been the development of two basic computer programs each of which possess unique capabilities which are not presently fully duplicated in the other.

As pointed out earlier, the most striking viscous phenomena which distinguish the flow around high-lift systems from the flow at cruise conditions are the possible existence of confluent boundary layers and of significant regions of separated flow at normal operating lift levels. The dual problems of separation and confluence have generally been approached separately in the course of developing analysis schemes for multielement airfoils, although the existence of a strong confluent boundary layer flow may have a substantial influence on the point(s) at which the flow may separate. A large body of experimental two-dimensional multielement airfoil data indicates that optimum high lift performance is obtained when gap and overlap conditions on the airfoil elements are set such that no regions of strong confluence exist (Fig. 23). However, any general multielement airfoil analysis should have the capability of accounting for merging shear layers in addition to its other capabilities. Without this capability it is impossible to properly perform analytical gap-overlap optimization studies, to account properly for boundary layer characteristics in the presence of even weak confluence which may effect both drag and separation location.

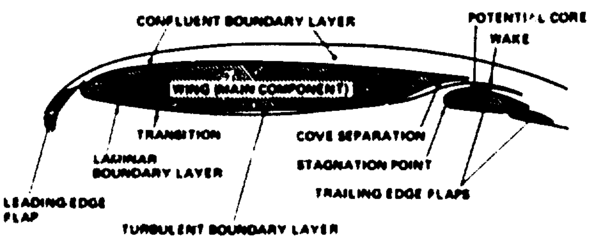

Figure 22. 2-D Viscous Flow Analysis and Design

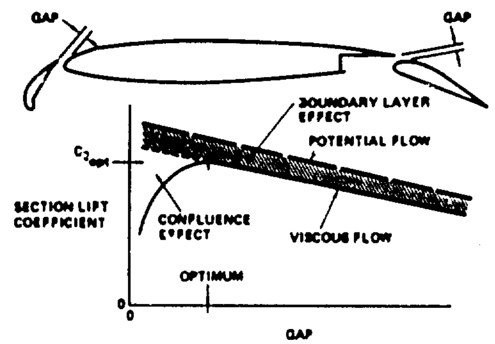

Figure 23. Influence of Airfoil Element Gap on Optimum Lift Performance

One approach to multielement airfoil analysis was originally developed by Goradia and his coworkers (ref. 15) at Lockheed-Georgia under the sponsorship of the NASA-Langley Research Center. This program was among the first attempts at analyzing the complex viscous flow about slotted airfoils and received worldwide distribution and usage. A unique feature of this multielement airfoil program was the model of the confluent boundary layer flow.

Over the years , the original version of the program was modified extensively to improve its predictions for different types of high lift airfoils. Many improvements, mainly in the area of the potential flow calculation, were made by researchers at the NASA-Langley Research Center. For this reason, the code generally has been referred to as the NASA-Lockheed multielement airfoil program.

This program has since been further developed by Brune et al (ref 16 & 17) partly under contract with NASA-Langley.

In many respects, this program, (with the Boeing modifications) is an excellent tool for the analysis of multielement airfoils with fully attached boundary layers. It remains useful both as a research tool and for those cases where its assumptions and limitations are non-restrictive in project use. It suffers from two major shortcomings, however. It is incapable of analysing separated flows and it has no inverse capability. A typical analysis result is shown in Fig. 24.

In the course of modifying the NASA-Lockheed code, Brune found the original confluent boundary layer analysis method to be inadequate. Therefore a new confluent boundary layer scheme was developed. (ref 16). It is a finite difference technique which solves the turbulent boundary layer equations and a two-equation model of turbulence due to Jones and Launder (ref. 17) known as the Kappa-epsilon model.

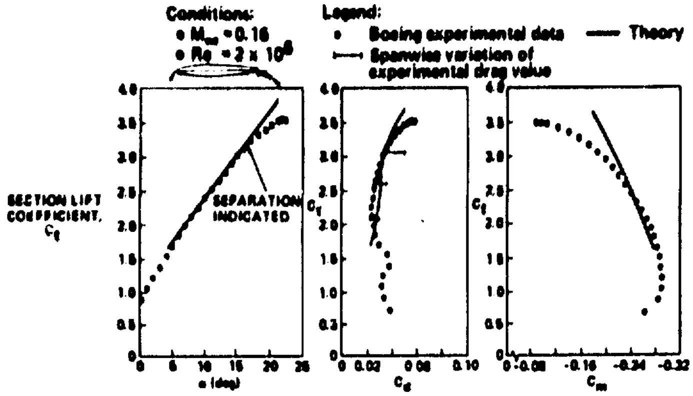

Figure 24. Lift, Drag, and Pitching Moment of a Boeing Four-Element Airfoil

One of the central difficulties in validating confluent boundary layer methods and viscous flow analysis methods for multielement airfoils in general, is the very sparse set of complete experimental data which exist in the literature for realistic airfoil sections. Thus a comprehensive test was conducted to acquire the data necessary to fully validate the new theory. In addition to force, moment and pressure distribution data, detailed information on mean velocity profiles and turbulence properties in the boundary layer at several chordwise stations was required.

Prior to conducting the test however, a survey of available instrumentation showed that existing equipment was inadequate to provide the high quality, detailed data required. Thus, an improved mechanical traversing mechanism was designed which would provide minimum disruption to the flow being measured and high position accuracy.

This new traversing mechanism and flow sensors are shown in figure 25. The traverse is self-propelled and is normally mounted on the side of the model opposite to the surface on which measurements are being taken. The traverse mechanism is equiped with four flow sensors: a pitot probe, two X-hot wires and a dual split film. Data from all sensors is acquired simultaneously. A description of this probe and samples of the very high quality data obtained are discussed in ref. 18 and 19. Sample data are shown in Fig. 26. The test-theory comparison of this data with the new confluent boundary layer program is shown to be excellent.

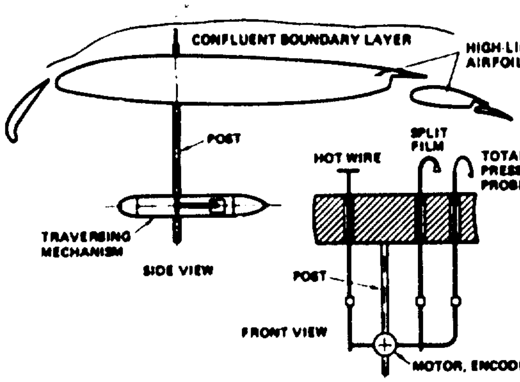

Figure 25. Sketch of Boundary Layer Traversing Mechanism Configuration for Minimum Flow Disturbance

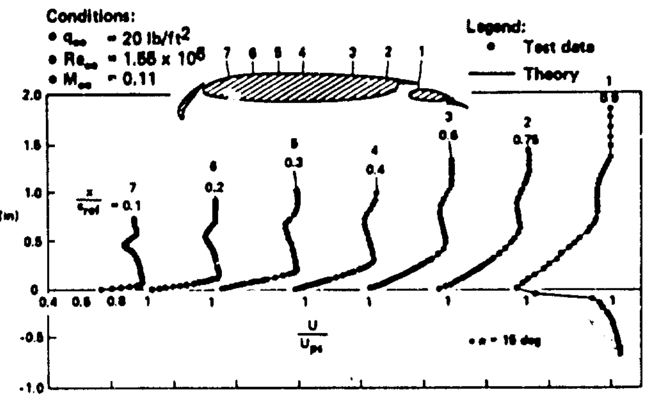

Figure 26. Confluent Boundary Layer Experiment

In most realistic applications, knowledge of section maximum lift coefficient is important, if not crucial, in airfoil design/optimization. In the absence of a computational capability to predict the effects of large scale flow separation, and hence maximum lift coefficient, heavy reliance must be placed on wind tunnel testing which has traditionally been conducted at Reynolds numbers an order of magnitude lower than actual flight conditions. This has generally led to substantial conservatism in the design, in efforts to reduce risk. In addition, the usual approach to computational design has been conducted by an iterative analysis process, wherein one begins with a baseline geometry and a desired performance goal and by analyzing the characteristics of the baseline geometry, obtained either experimentally or computationally, attempts to determine "intuitively" how the initial geometry ought to be modified to meet performance goals. Whether conducted in the wind tunnel or on the computer, the process remains largely one of "cut-and-try."

It has long been realised that a more rational approach to the aerodynamic design problem would be to begin with a realistic set of performance objectives and constraints, and derive the pressure distributions and other flow characteristics necessary to meet these objectives based on boundary layer theory. With the desired flow characteristics established, one can then extract by computation the geometry necessary to produce these desired flow characteristics. This "inverse" or synthesis process, while conceptually simple and desirable has only become practical with the advent of large digital computers.

With these considerations in mind, M. L. Henderson developed a versatile computer program system (ref. 20) which would allow both the analysis and design of multielement airfoils with inclusion of the effects of separation in the analysis mode and inverse boundary layer techniques for pressure distribution synthesis in the design mode.

The Subsonic Analysis Section System (SASS) is based on two-dimensional higher order panel method algorithms for potential flow and integral boundary layer methods for viscous flow computations. The two important components of the separation modeling are the determination of the separation point(s), and and the streamline displacement caused by the separated wake. This latter problem is handled by introducing a separation cavity whose contours may be determined without recourse to detailed calculations of the complex interior physics. This wake displacement body is added to the bare airfoil geometry, and the whole "equivalent body" may then be analyzed in potential flow to predict separated flow airfoil section performance. This procedure is described in detail in refs. 3 and 20. Some typical test-theory comparisons are shown in Figure 27.

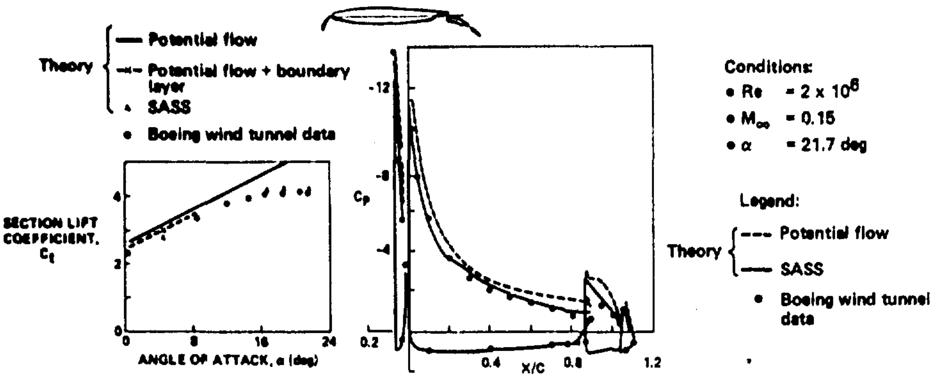

Figure 27. Predicted Airfoil Data From Subsonic Analysis Section System (SASS)

The overall program system also incorporates provision for a separate inverse boundary layer method for the design and evaluation of pressure distributions for input to the design mode of the program. This inverse boundary layer method, (ref. 21 and 22) is also a valuable tool in its own right.

HIGH-LIFT FLOW CORRELATION AND PREDICTION TECHNIQUES

At present there is no analytic method capable of solving the three-dimensional viscous flow about wings, let alone full aircraft, in high-lift configurations. Even if or when this capability is developed it will likely be time-consuming and expensive to use on a production basis. Thus there will always be a need for:

- Correlation methodology for two-and three-dimensional flows which allow (where appropriate) the use of simpler, more economical two-dimensional viscous methods loosely coupled to three-dimensional potential flow techniques.
- Semi-empirical techniques for the prediction of full-scale aircraft high-lift performance from wind tunnel data and from the performance of previous aircraft of similar geometry.
- Techniques for the prediction of both wind tunnel and flight level high-lift performance of preliminary design configurations for which no specific wind tunnel data exists.

The problem of establishing rational methods for connecting the results of three-dimensional potential flow with two-dimensional viscous flow analyses has been an important part of the high-lift research effort. As a major part of this effort it has been necessary to establish the correlation between two-dimensional multielement section characteristics with the corresponding sections on three-dimensional wings as influenced by sweep, induced angle-of-attack and camber effects, and spanwise components of boundary layer flow.

As an example of early correlation methodology work, it was found that "simple sweep theory" type corrections to two-dimensional results, which are rigorously valid only for thin wings of constant chord and infinite aspect ratio, should be replaced by the more theoretically correct method due to R. C. Lock (ref. 23) which explicitly accounts for taper and finite aspect ratio effects.

With the advent of the DVM Lifting Surface Theory program, Goldhammer was able to achieve a substantial advance in correlation/prediction methodology. For the first time it became possible to reliably obtain potential flow results for high-lift configurations representative of actual transport aircraft.

An example of what Goldhammer was able to achieve with combined use of programs DVM and SASS (corrected for sweep), to predict high-lift wing/body characteristics beyond the linear portion of the lift curve is demonstrated here. The assumptions made in this example are that airfoil section characteristic dominate the lift behavior of the wing; and that even in cases where the flow may be locally separated, spanwise boundary layer flow effects can be neglected.

As demonstrated earlier, use of the DVM program for cases of highly deflected part- or full-span flaps, with separation at normal operating conditions, leads to a substantial overprediction of lift. However, by analysing "critical 2D sections" of the wing (located at "peaks" in the span loading distribution) using the SASS program with its separated wake modeling capability, an "effective" viscous flap deflection angle can be determined as shown in Figure 28.

When this new effective viscous flap deflection is input to the potential flow analysis (DVM) the result is a dramatic improvement in the test-theory comparison of span loading shown in Figure 28.

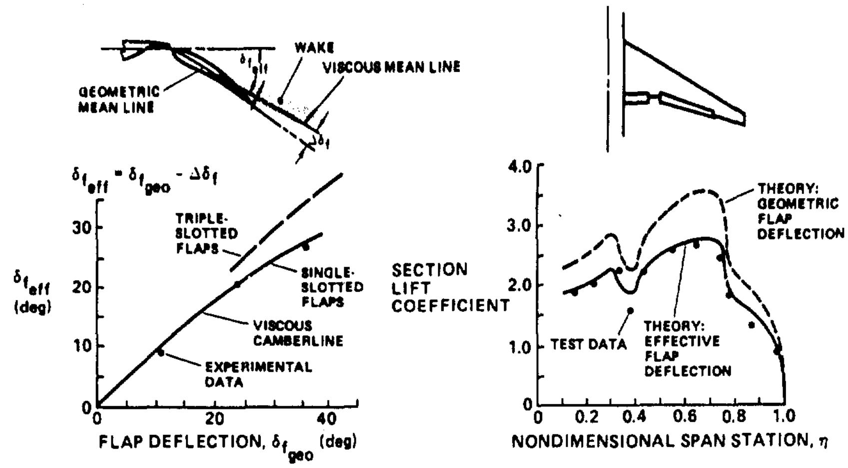

Figure 28. Effective Flap Deflection—Influence on Span Loading

Perhaps a more remarkable outcome of this sort of analysis was the fact that applications of the DVM program to a variety of other transport type configurations showed a repeatable (to first order) correlation between effective and geometric flap deflections for a given number of elements in the high lift system. This led to the tentative construction of the graph relating effective and geometric flap deflections shown in the figure. These relations hold only for standard wind tunnel level Reynolds number, although a comparable set could be constructed for flight levels.

It should be noted that the work reported so far has been largely directed toward providing computational tools to project level engineers for use during the detail design phase of an airplane development program. This goal continues to be important and has been remarkably successful. As reported in ref. 24, the combined progress in 3D potential flow analysis and 2D viscous flow analysis and design when coupled with progress in 2D-to-3D correlation methodology has lead to a quasi-3D viscous flow analysis and design capability for multielement wings. This design process which relies heavily on the use of 2D inverse methods is shown diagramatically in Fig. 29, and will be demonstrated in more detail later in this paper.

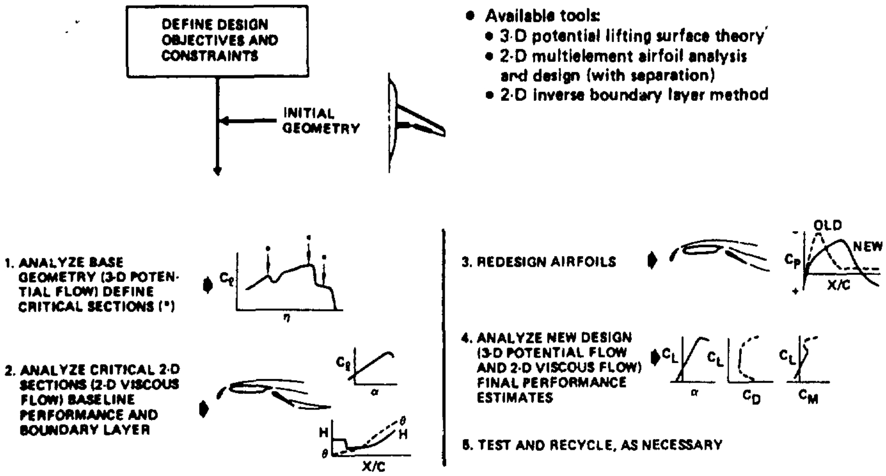

Figure 29. High-Lift Analytical Design Procedure

As shown in the overview diagram (Figure 30), at the detail design level, computational methods intended to complement extensive testing must be highly accurate. Thus costs may be high, although fully justified if an enhanced design process results.

Design level	Accuracy required	Turnaround time	Cost	Method
Conceptual	Approximate (±10-20%)	Negligible	Negligible	Handbook and calculator
Preliminary	Good (±5-10%)	Rapid	Low	Semiempirical
Detail (project group)	High (±2-5%)	Reasonable	Moderate	Full analysis and design Viscous 2-D Inviscid 3-D

Figure 30. Low-Speed Aerodynamic Prediction Methods

In a preliminary design phase of aerodynamic configuration development, computational methods are also of major importance. In this case, however, where many continually changing configuration variables must be considered and their effects on the global aerodynamic characteristics readily evaluated, the conflicting requirements of computational accuracy and ease of use, rapidity of turnaround and low cost make the development of appropriate computational methodology challenging.

The need for modern predictive methodology appropriate to preliminary design level aerodynamic analyses remains, however. Recognizing the limitations of existing theoretical tools, better computationally based predictive methodology can be devised if one accepts certain underlying assumptions, as discussed in ref. 25.

A method devised to fill the block for a preliminary design level predictive tool in Figure 30 is semi-empirical and relies on two computer programs. The new method is made possible and practical by the existence of the DVM potential flow computer program specifically developed for the analysis and design of multielement high lift configurations described previously.

The second program in the system, is identified as AePP (Aerodynamic Prediction Program). AePP is a highly automated system of bookkeeping, interpolation/extrapolation, scaling and post-processor routines which produce the predictions of global aerodynamic characteristics of a configuration in a subsonic viscous flow.

The structure is based on a framework in terms of potential flow lift curve, pitching moment, induced drag and span loading provided by independent runs of the DVM program, as shown in Figure 31, and provides the engineer with two options:

Option 1: By numerically comparing DVM lifting surface theory predictions on a baseline configuration for which experimental data exists with experimental data, using AePP, the effects of changes in the baseline geometry (e.g., flap span, flap chord, number of flap elements) can be estimated with good accuracy. In this case the full procedure shown in Figure 31 is used.

Option 2: In the case where no explicit baseline experimental data exists, combining generic empirical data stored in AePP with DVM lifting surface theory results for the geometry of the configuration to be evaluated, provides estimates of global aerodynamic characteristics of adequate accuracy for preliminary design purposes.

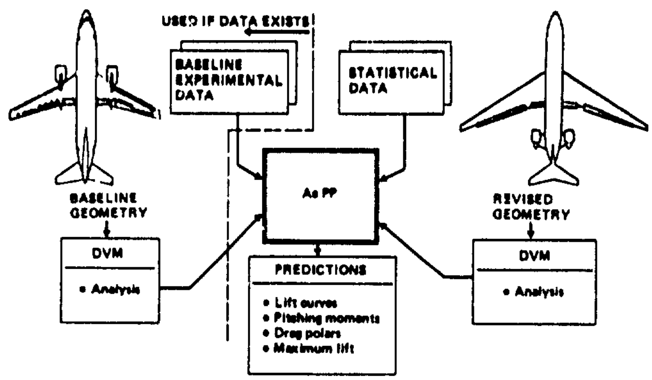

Figure 31. Aerodynamic Prediction Procedure (Low-Speed)

An outline of the overall method and its program elements is shown in Figure 31. How the method works is shown in Figure 32. A complete discussion of the assumptions made and how the empiricism described above is incorporated in the method together with several examples of application are described in ref. 25.

One example from this reference is reproduced here to demonstrate the capability of the basic approach. In this example, Figure 33, wind tunnel data from a Boeing 767 was used to predict the lift, drag and pitching moment (tail-off) characteristics of a Boeing 737-300. The quality of the predictions appear quite acceptable for preliminary design purposes.

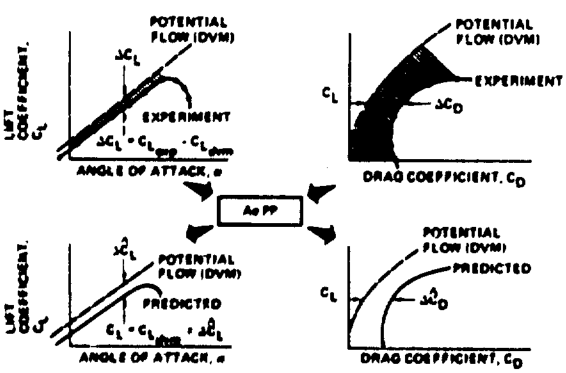

Figure 32. Low-Speed Aerodynamic Prediction Procedure

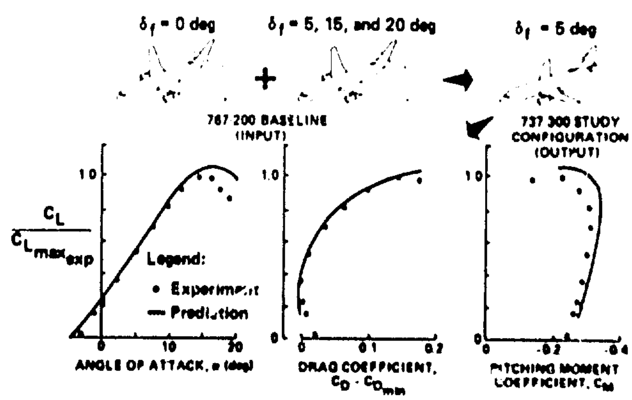

Figure 33. Prediction of a Boeing 737-300 From a 767-200

WAKE VORTICES AND VORTEX/BOUNDARY LAYER INTERACTIONS

An important high-lift problem is that associated with the lift-induced trailing vortices that roll up in the wake of large airplanes and are persistent and sufficiently powerful to be hazardous if other airplanes encounter them before they decay. The problem is most acute in the traffic patterns of

airports, where both aircraft congestion and vortex intensity are greatest and where maximum air traffic control is required. Although it is important to predict such phenomena, and a good deal of research has been devoted to the problem, wake vortex alleviation has up to now not been a factor in high lift system design.

In addition to the classic wake vortex problem, a number of other practical high lift problems associated with the formation and shedding of large scale vortices from various components of an aircraft have been identified. Among these are the effect of large vortices shed from nacelle/strut combinations, strakes, etc., on the aerodynamic characteristics of the wings and empennage, and most particularly the interaction of such vortices with the boundary layer flow on the wing. While in some cases these vortices may be beneficial, in other important cases they may seriously degrade high-lift performance.

The approach to vortex research at Boeing has been the development of predictive technology, and experimental techniques for the measurement of vortex flows. The general objective is to understand and predict the formation, growth and decay of a wide range of large scale vortex flows as they interact with other components of the airframe itself and/or subsequently influence other aircraft in proximity to shed vortex wakes. The ultimate objective is to find means of either controlling the formation or intensity of large scale vortices so that they interact favorably or with minimum penalty with other components of the generating airframe.

Since the state-of-the-art in modeling realistic vortex flows (c.f. Fig 34) is still primitive, particularly in the case where vortices interact strongly with a boundary layer, the majority of the work done so far in this area has been experimental. The emphasis has been on:

- Development and exploition of a number of flow field visualization techniques for the diagnosis of complex viscous/vortex interactions and shed vortex wakes.
- Development of experimental data bases for transport aircraft configurations in high-lift/high angle-of-attack conditions. These efforts have been conducted to:
  - Provide necessary data to validate the extension of codes like PANAIR to analyses of multielement wings.
  - Clarify the physics of vortex formation and interactions as generated by high-lift configurations.
  - Establish an experimental data base with which to compare current efforts to model three-dimensional separated flow.
  - Provide data for wake/downwash prediction at the plane of the empennage, particularly during operation at high-lift/high-angle-of-attack conditions.

A great deal of flow field visualization and diagnostic work has been done ranging from tests in water tunnels to subsonic wind tunnels. The conclusion from tests conducted in water tunnels has been that, while yielding useful results for certain types of configurations (e.g., fighters with wings with sharp leading edges), the low Reynolds numbers typical of such testing make such experiments nearly useless for transport type configurations. A far better approach has been to use flow field visualization techniques recently developed for conventional wind tunnels. These techniques include:

- The Boeing developed Wake Imaging System (WIS) described in ref. 26. Typical WIS total pressure survey data is shown in figure 34 in a black-and-white reproduction. The actual result, obtained in about four minutes of survey time and available immediately, are in the form of color polaroid photographic prints.

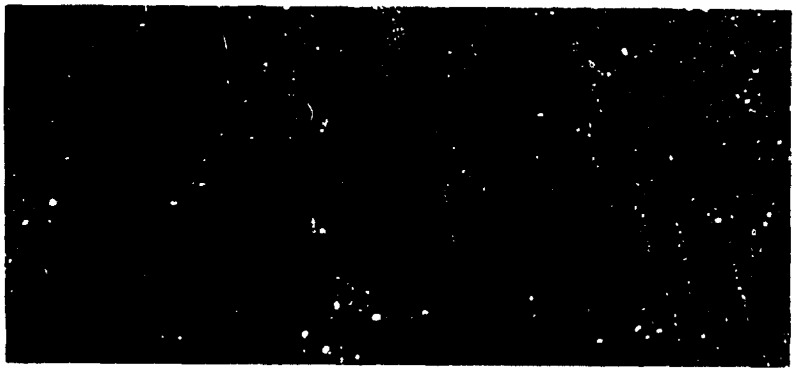

Figure 34. Wake Image System (WIS) Survey Behind a High-Lift Wing

- The five port probe (ref.27) which can give survey data similar to the WIS, with the additional advantage that fully quantitative data, three velocity components and total pressure are provided in minimum post run time. This latter technique has been used very effectively to map wakes as shown in Fig 35, and a full discussion of recent test results using this technique is reported in refs. 27 and 28. These experiments have shown good correlation between WIS and five port probe data, both of which also correlate reasonably well with limited laser velocimetry measurements.

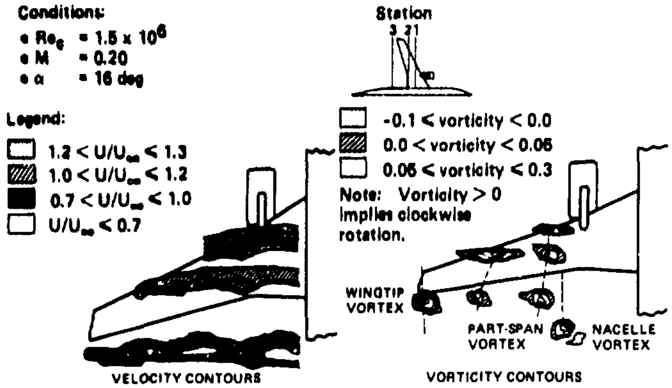

Figure 35. Five-Port Probe Survey Data

The cited references give further details on these flow visualization techniques and some additional results will be discussed in the next section on practical applications.

In an appropriate experimental approach to complex viscous/vortex, separated flow and/or wake problems, it is important to recognize that a "full set" of data is usually necessary, and such a full data set includes forces, surface pressures and both surface flow and flow field visualization. It has been our experience in diagnosing complex flows that given a number of equally experienced interpreters evaluating the same surface flow pattern, one often gets as many interpretations as there are evaluators.

To evaluate the surface flow in a systematic way mathematical topology ("critical point theory") as developed by several investigators has been of considerable value. Critical point theory has the virtues of rapid application, and it clearly establishes which flow interpretations are kinematically feasible.

The technique is well described by Peake and Tobak (ref. 29) and Dallmann (ref 30). A typical result of work due to Brune (so far unpublished) of extensions to high-lift and multielement wing configurations is shown in Fig. 36.

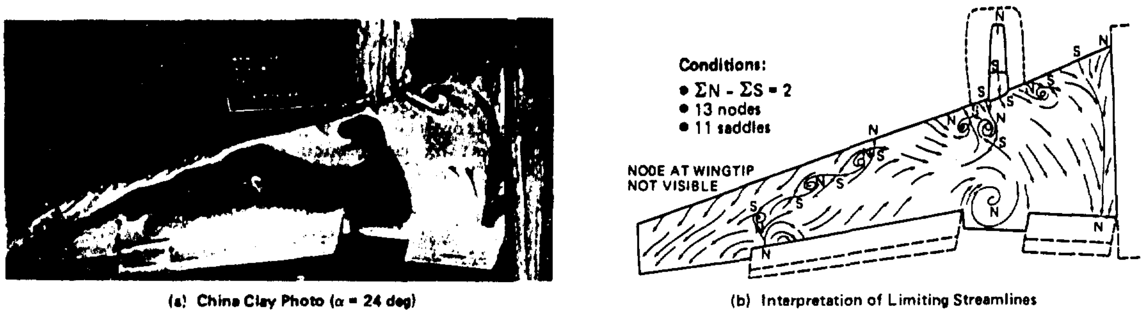

Figure 36. Interpretation of Separated Flow Pattern, Using Critical-Point Theory

SOME APPLICATIONS OF BOEING HIGH-LIFT DESIGN METHODOLOGY

In the preceding sections of this paper a great deal of progress has been reported in the development of improved methodology, both computational and experimental, for the design and analysis of transport aircraft high-lift systems. In order to complete the discussion and to clarify several of the issues raised earlier, two examples of applications of this improved methodology to practical design problems have been selected.

A Redesign of the Boeing 747 High-Lift System

The first example was selected because it demonstrates the way in which the general quasi-three dimensional viscous flow design methodology (Fig 29) with its strong reliance on the use of inverse methods, was used to evaluate a complex design problem. The problem posed was: Given the wing of the existing Boeing 747, is it possible to simplify the triple slotted flap/variable camber Krueger high-lift system without degrading the approach speed. Further constraints were:

(1) The cruise aerodynamic configuration must remain unaltered.
(2) Major structural modification outside the flaps would not be allowed.
(3) Handling characteristics should not be degraded.

As shown in Fig. 37, the baseline geometry was first analyzed in potential flow using the DVM Lifting Surface Theory. This yielded the span loads at various values of lift coefficients. From the span loads, the "critical 2D sections" were selected and evaluated using the 2D multielement airfoil code SASS. These results corrected for sweep are shown in Fig. 38. Additional information obtained from these analyses are viscous flow pressure distributions and details of the boundary layer characteristics. At this point one has the basic data necessary to begin the redesign effort.

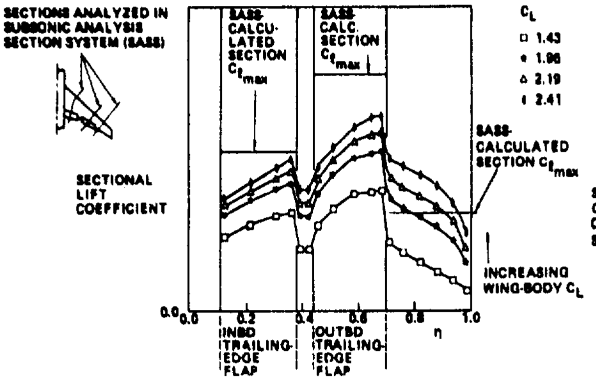

Figure 37. Spanloading on Baseline 747-200, Flaps 30, Calculated With SASS

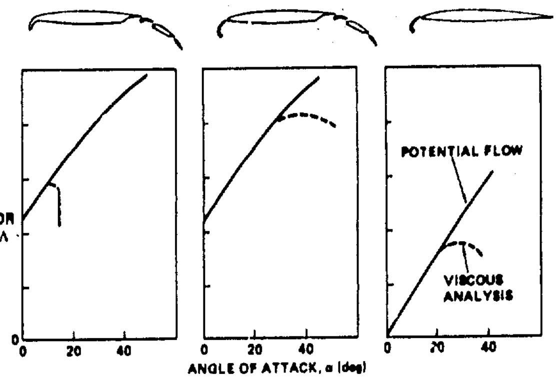

Figure 38. SASS-Calculated Sectional Lift Curves, $\delta_f = 30$ deg

Using the 2D inverse boundary layer method, improved viscous flow pressure distributions are derived for the various elements of the multielement airfoil ensembles. These design point pressure distributions are then used in the inverse mode of the SASS program to generate new airfoil geometries. These new geometries are a combination of revised surface contours and/or modified flap gap, overlap and deflection relationships.

With the new geometry established, these sections are analyzed in the SASS program to obtain full section lift curves, including the effects of flow separation from one-or more airfoil element. Typical final results are shown in Figures 39.

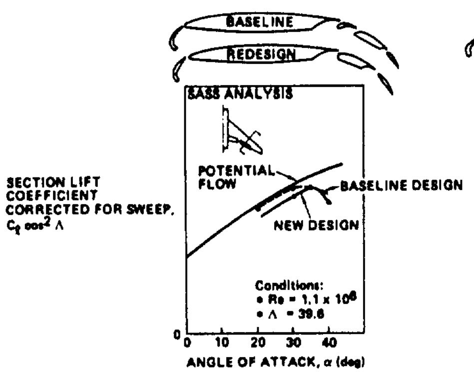

Figure 39. SASS Analysis of Baseline and Redesigned Flaps

As a final step, if the resulting new geometry differs substantially from the baseline case, a reevaluation of the total high lift systems in the DVM program can be conducted to assure that a "converged" design solution has been achieved and this data can be used to estimate the new wing/body maximum lift coefficient and/or lift-drag ratio.

An interesting result of the present example is shown in Fig. 39. The new double slotted flap does indeed yield the same section maximum lift coefficient as the baseline triple slotted system but more important however, at a given angle of attack the lift coefficient is lower for the redesigned system than for the baseline. This means that the net result of integrating this revised section into the system would be that the aircraft would have to approach at higher angles-of-attack to maintain the same approach speeds. In practice this is not possible due to tail strike limitations. For this reason, the results of this particular exercise remain of largely academic interest and the new configuration was not tested. The example does demonstrate clearly, however, the power of the new analytic approach to high-lift design.

Transport Aircraft Maximum Lift Performance Improvement

The second application example to be discussed is of interest for several reasons.

1. Both wind tunnel and flight test validation results exist.
2. The full computational methodology previously described was applied to a difficult flow problem involving a complex airplane geometry.
3. While the computational methods alone were inadequate to cope with the full problem, when used to augment and guide the wind tunnel testing, they provided the crucial element in achieving a difficult aerodynamic goal.
4. An approach to partially circumvent some major limits of conventional low Reynolds number testing in high-lift system development was demonstrated. This approach can only be pursued efficiently by application of computational techniques.

The objective was to retrofit the basic Boeing 707 airframe with four large diameter high-bypass ratio turbofan engines with minimum modification to the remainder of the airframe and without an off-design (i.e., low-speed) performance penalty. The new nacelles were compatible with the baseline airframe, provided the nacelle struts of the new installation were shorter than those of the baseline, resulting in the nacelles being placed in closer proximity to the wing. Wind tunnel tests comparing the baseline and retrofit airplanes showed no low-speed performance penalty. Corresponding flight tests showed a 10

percent loss in airplane maximum lift capability. The comparison results are shown in Figure 40. Further, based on low Reynolds number wind tunnel force data alone, there appeared to be no obvious experimentally derivable aerodynamic fix.

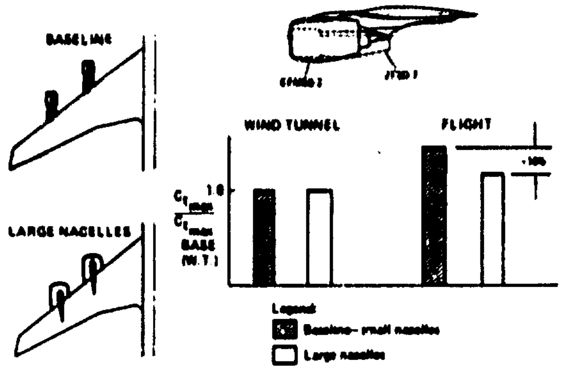

Figure 40. Nacelle Influence on $C_{\ell_{max}}$

The puzzle regarding the cause of the lift loss was solved by additional wind tunnel testing with particular emphasis placed on carefully documented flow visualization. Nacelle-on and -off tests clearly showed (Fig. 41) that flow separation occured on the sides of the large diameter nacelles at high angles of attack and high flap deflection conditions, leading to the formation of large vorticies which flowed streamwise over the wing. While the section characteristics of the wing were very strongly Reynolds number scale dependent, the paths and strength of the nacelle shed vortices were almost scale independent as a comparision with flight test showed (fig 42). Further, under certain conditions, the vorticies interacted in an unfavorable way with the boundary layer on inboard sections of the wing downstream. As a result, at wind tunnel Reynolds numbers, the maximum lift characteristics of the wing were dominated by the outboard section characteristics. At flight level Reynolds numbers, the outboard wing sections benefited from the increased Reynolds number so that maximum lift was limited by the unfavorable inboard wing boundary layer/nacelle vortex interaction. Thus, the two configurations, both with identical wings and high-lift systems, exhibited almost equal maximum lift performance in the wind tunnel, but not at flight conditions. Subsequent analysis of the wing using the quasi-3D viscous analysis approach described earlier further validated and clarified this diagnosis.

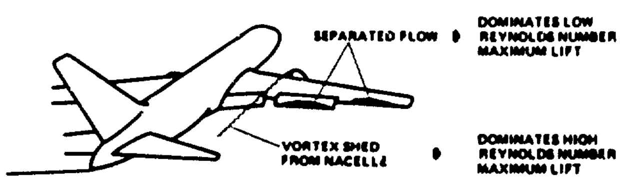

Figure 41. Stall Mechanisms at High and Low Reynolds Number

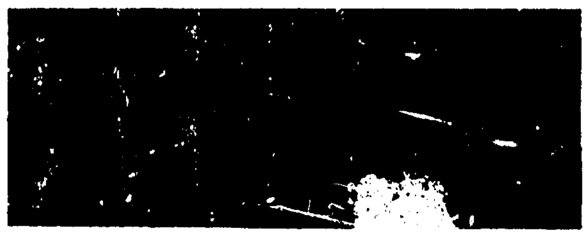

Figure 42. Nacelle V...

Thus, the puzzle was solved, but the problem was not. Having observed that the wind tunnel, using a model which carefully simulated the full scale geometry of the proposed configuration, could not duplicate the necessary flow phenomena, the traditional approach would be to embark on an expensive and time consuming flight test program, with the fear that a substantial revision of the baseline high-lift system might prove to be the only satisfactory solution. However, with the availability of computational tools, a quite different approach became feasible.

This approach was to simulate the full scale aerodynamics, rather than the full scale geometry in defining the parts of the wind tunnel model. While conceptually appealing, this course is almost impossible to follow unless one has sufficiently powerful computational tools with design capability.

In the case under discussion, the full scale simulation was rather crude but extremely effective. Having determined both by flow visualization and analysis that the low Reynolds number stall characteristics were driven by outboard wing section characteristics, it was a straightforward procedure to design an alternate, non-standard, leading edge device (Fig. 43) which could be fitted to the outboard wing of the wind tunnel model. In this way, the outboard wing behaved at wind tunnel Reynolds number very much like the full scale wing did in-flight, i.e., nacelle vortex/wing boundary layer interactions determined the stall in the wind tunnel.

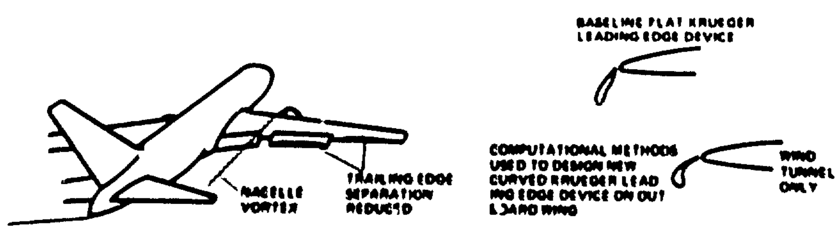

Figure 43. Wind Tunnel Test To Find Solution

Having adjusted the wing's stall patterns in the wind tunnel, attention turned to the necessary modifications of the nacelles to improve the maximum lift performance. Additional reliance on flow visualization utilizing the wake imaging system lead to development of a set of nacelle mounted vortex control devices (VCDs) which finally solved the problem without further change to the baseline high-lift system. These devices were subsequently flown on the full scale airplane with satisfactory results, as shown in Figure 44.

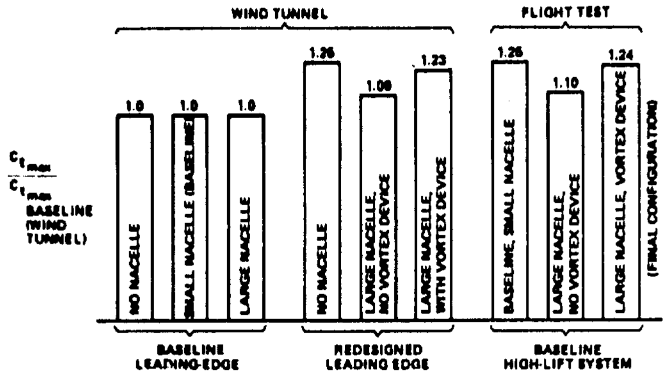

Figure 44. Maximum Lift Comparisons

CONCLUDING COMMENTS

An outline of low-speed/high-lift aerodynamic research at Boeing, and the quasi-3D viscous flow computational methodology developed for the analysis and design of transport high-lift systems was presented. To demonstrate the overall utility of this methodology, two examples of its application to practical, project oriented design/analysis problems were described. The important conclusions to be drawn from these examples are:

1. Modern high-lift computational methods have become sufficiently well developed to allow a designer to use these new methods in a greatly improved (compared to experimental/analytical cut-and-try) design process.

2. Since, in the forseeable future, management cannot be expected to make decisions which risk millions of dollars based solely on "analytic wind tunnel" results, the objective of a practical research effort must be to derive computational tools which will both augment and improve the efficiency of what remains an experimental process. With the parallel development of improved flow visualization techniques, the experimental process has been advanced as well.

3. The role of the wind tunnel will change as computational methods of increasing power become available. Much routine parametric evaluation can now be conducted with the computer, with the wind tunnel acting as both the vehicle for visualization of complex flows and the final arbiter of predicted results. Thus theory and experiment form a necessary complementary pair.

4. Modern computational methods now allow the high-lift system designer to do many of the things that were once conceptually possible, but impractical due to either lack of physical understanding or budget limitations. Both computational exercises described and the modeling of "full scale" aerodynamics rather than full scale geometry in the wind tunnel, are examples of these emerging capabilities.

5. Most of the work described in this paper has related to transport aircraft with unpowered high-lift systems. Much of the technology described (most particularly the improved flow visualization techniques) is fully applicable to military aircraft and powered lift concepts. As the methodology described matures, attention will logically be devoted to extending these kinds of capabilities to the full range of future high-lift schemes.

It would be satisfying to be able to say that we limited ourselves to unpowered high-lift systems due to the large volume of material available and that a comparable paper could be written on powered-lift systems. Unfortunately this has not been the case. Despite the flurry of activity in powered-lift in the early to mid-1970's, as evidenced by the flight of four different powered lift airplanes only limited analytical development has been undertaken. This is still a largely virgin territory awaiting the inspired researcher.

While the above comments are specific to the Boeing high-lift effort, it remains to make some more general observations relating to the issues identified in the introduction of this paper. Central of these was the question of the tools available to the high-lift designer and those which remain to be developed. Many of the aspects of this question have been addressed in previous sections of the paper and need not be summarized again here. One matter of interest does deserve attention here however.

At the conclusion of his Wright Brothers Lecture A.M.O. Smith left us with his list (circa 1974) of the ten pressing theoretical problems in high-lift aerodynamics. In light of the progress reported in this paper, it is of interest to review these ten issues and comment on the progress made on each in the intervening period. We may then propose a new list of our own.
A.M.O. Smith's list was as follows:

1. Very general calculation of three-dimensional laminar and turbulent flows.
   This must stand as an important on-going effort despite years of effort and advance. It should be noted that success in this area is still strongly coupled to our ability to solve the inviscid flow portion of the problem and here the complexity of the geometry of practical

aircraft high-lift systems still presents major obstacles both aerodynamically and in geometry definition. The capability to predict trailing edge separation on three-dimensional configurations is also emerging, but the capability to predict vortex/boundary layer interactions remains very primitive.

2. Calculation of flows involving partial separation in the rear.
Here great progress has been made in 2D flows (c.f. Henderson, ref. 20, Bristow, ref. 31, and Mani, ref. 32). This is an area where much progress may be made in the near term in three dimensional flow without recourse to solution of the full Navier-Stokes equations.

3. Practical calculation of flows involving forward separation bubbles.
Much detail work remains to be done in this area. While apparently a mere footnote to the overall high-lift problem, as long as wind tunnel tests continue to be conducted at "low" Reynolds numbers, the capability to predict the formation and effect of laminar separation bubbles remains an important, imperfectly developed, capability.

4. Practical calculation of flows involving shock-boundary layer interactions.
Slow, but steady progress has been made on this fundamental problem (ref. 33) but its relevance to the low-speed high-lift problem would seem obscure. "Supercritical" leading edge devices on transport aircraft are items to be avoided in our experience.

5. Calculations of viscous flow around the trailing edges of wings and bodies.
Despite the work of, for example, Melnik (ref. 34) this problem remains to be fully resolved and remains, as it did for Smith a decade ago, a major annoyance.

6. Further development of inverse methods.
Substantial progress has been made for 2-D cases. For 3-D the PANAIR technology has great promise. It may also be noted that development of such methods is less than half the problem. Teaching engineers, accustomed to "design by repetitive analysis" to use inverse methods effectively is as large a problem and requires a great deal of further understanding and education.

7. Drag of multielement airfoil systems.
Squire and Young still reign in this area and progress of real substance remains to be made.

8. Practical calculation of merging boundary-layers, wall jets and wakes.
With the completion of the combined theorical/experimental work by Brune (ref 16 & 19) reported here, this problem seems to have reached the state-of-the-art in overall 2D viscous flow computational capability. Having done the work we observe that it may have been a problem of limited priority in retrospect. Analytic gap/overlap studies are nearly as expensive to perform computationally as experimentally, and aside from evaluating the adverse effects of imperfectly sealed slats, etc, the analysis capability is of rather limited utility.

9. The analysis of flows over swept wings on which a leading-edge vortex is developed.
This is a major area of interest and substantial progress has been made for highly swept wings with sharp leading edges. For moderately swept wings with rounded leading edges where vortices are less well defined much work remains to be done.

10. Three-dimensional transonic calculations, particularly for arbitrary wing and wing body conbination.
Very great progress has been made here, largely with reference to cruise configurations. This topic is not within the scope of the present paper and it seems to us of less relevance for transport type high lift systems.

In quick summary then we see a decade's progress. It remains only to propose a menu of our own for further work. Our shopping list is as follows:

1. Very general calculation of three-dimensional laminar and turbulent boundary layers.
2. Computation of three dimensional separation,
3. Drag of multielement wings.
4. Further development of inverse methods.
5. Wake and downwash prediction from 3D multielement configurations.
6. Vortex/boundary layer interactions.
7. Propulsive lift analysis.
8. 3 D flow visualization and measurement techniques.
9. Modeling of swept wing leading edge flow with separation
10. Analytical buffet prediction

Further comments on the above list seems superflous in light of the preceding discussions and the authors want to end this paper with the hope that the coming ten years will show as spectacular progress as the last ten.

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